New Life in Fatigue

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HOUSTON, WE HAVE A PROBLEM ...

Fatigue in High-Speed Aluminium Ships

a total stress concept and joint SN curve formulation

21-11-2011

Introduction

- For many years, aluminium alloys have become the standard for high speed ships.

L_{pp} = 12 …15 [m]

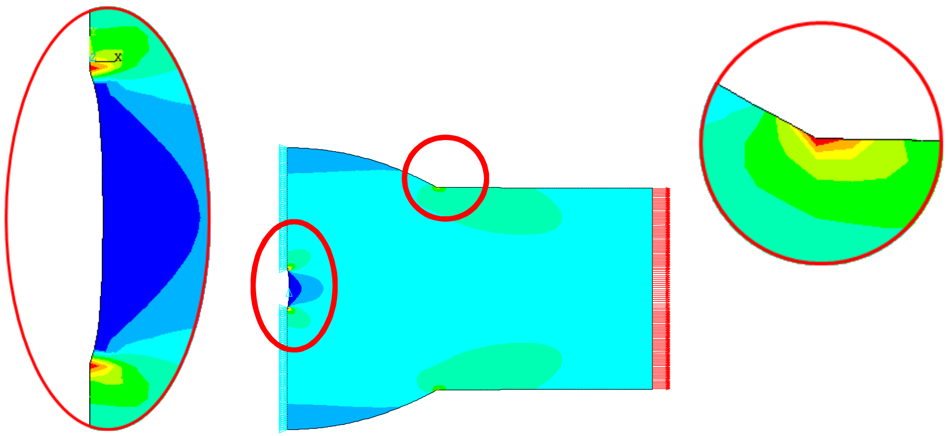
F_n ~ 1.0 [-]

- Primary joining method for ship structural components:

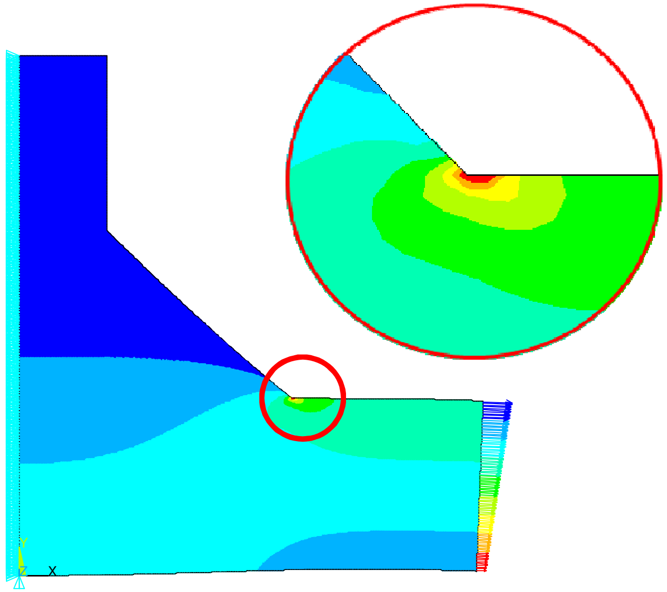
ARC-WELDING

fracture toughness:
aluminium << steel

Introduction



- Arc-welding:
  - ➢ Reduces fatigue strength
  - ➢ Fillet welds and butt welds introduce NOTCHES (stress concentrations):



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- ➢ Dynamic loading

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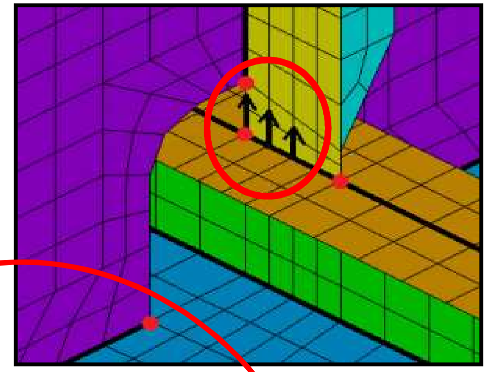
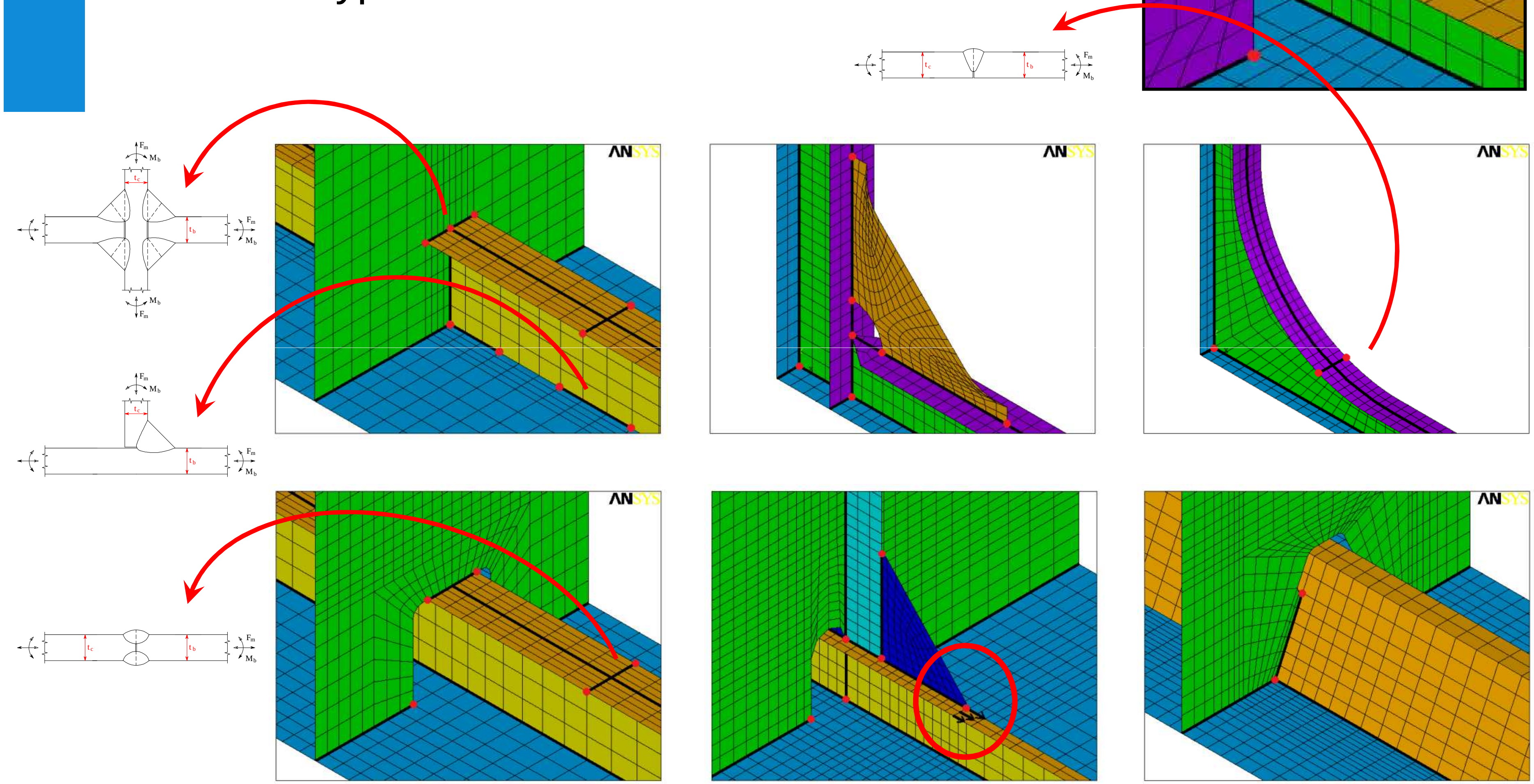
- ➢ WELD LINES fatigue governing parts of ship structure

Introduction

- Some typical structural details: weld line + ends

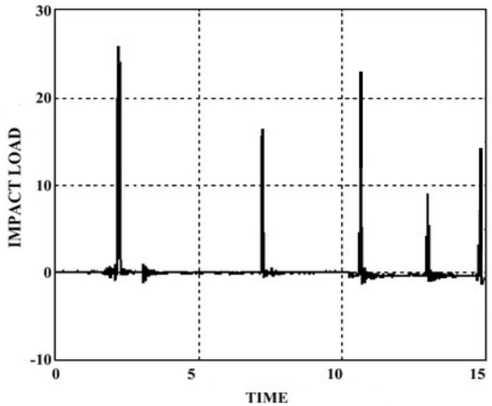


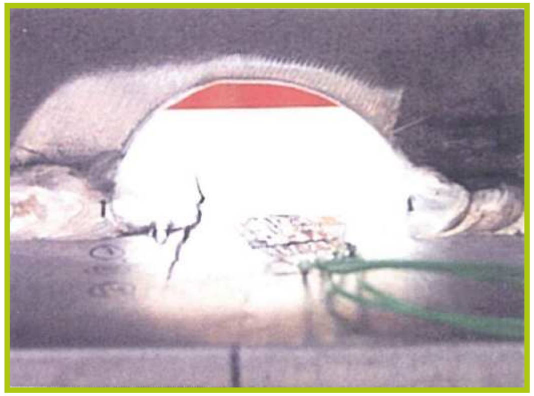


Introduction

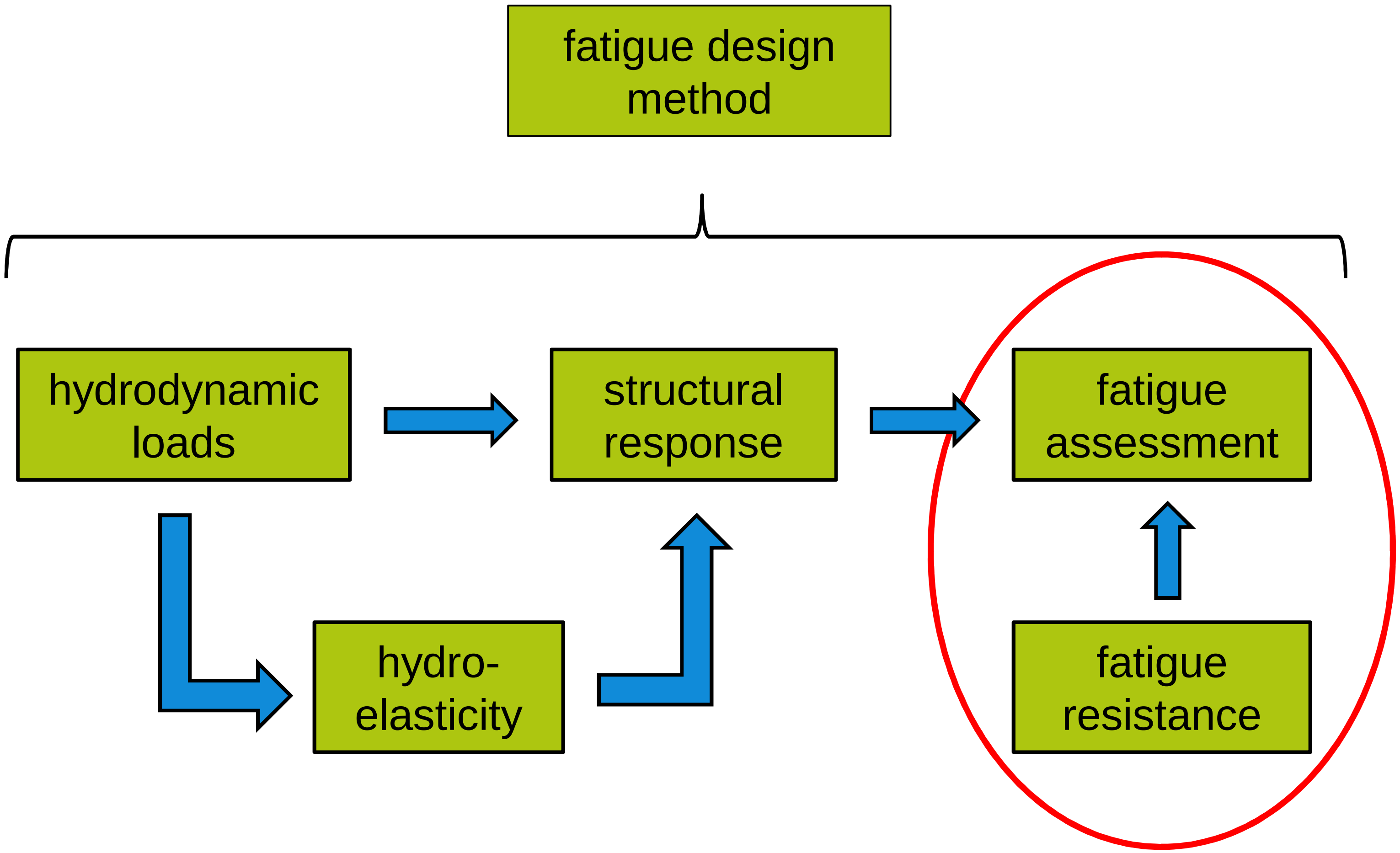
- Maritime Innovation Project (MIP): VOMAS
- Consortium: Damen Shipyards, TUD, Marin, TNO, BV, LR, ABS, USCG

For high-speed aluminium vessels, a practical, efficient methodology to predict (impact induced) fatigue in an early design stage does not exist.



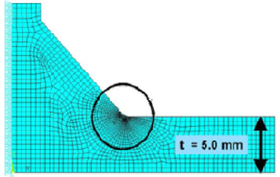


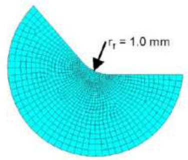
Introduction



Motivation

- Fatigue life prediction concepts

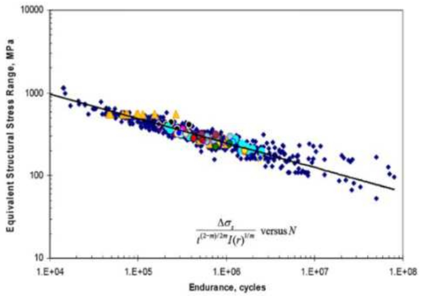




- 1 SN curve
- fictitious notch radius transforms nominal stress fatigue strength systems in a uniform local stress value
- fine solid mesh

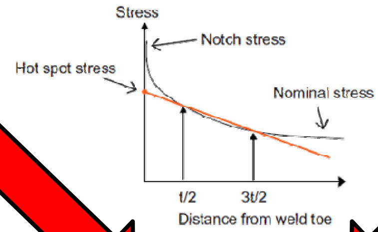
Battelle SS approach:

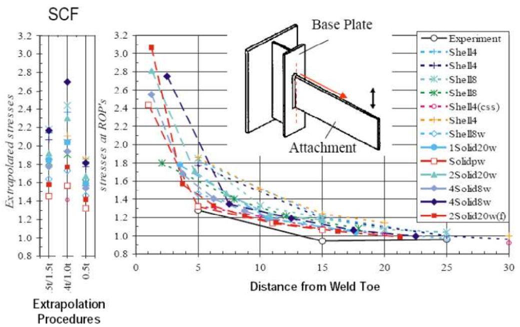
- master SN curve
- mesh insensitive
- design environment



structural (hot spot) stress concept

(fictitious) notch stress concept

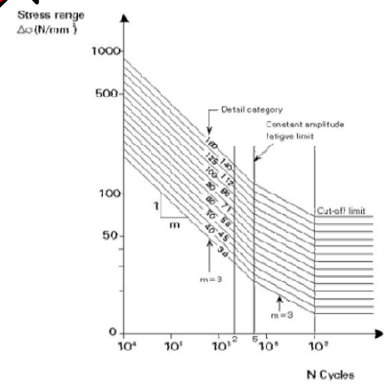




HSS approach:

- extrapolation method sensitive
- fine mesh
- 1 or 2 SN-curves

nominal stress concept



- ∞ SN-curves / detail cat.
- x SN-curves + SCF
- design environment

Motivation

- Some modelling considerations:
  - ➢ Ship structure = shell plated structure
  - ➢ Governing parameter: $t_b << (a,b)$

    single SN curve with stress based through-thickness criterion
  - ➢ Shell FE environment: no weld modelling
  - ➢ WELD LINES / basic joints / failure locations
  - ➢ Include characteristic NOTCH crack propagation behaviour
  - ➢ Relation to LEFM approach: welding process induced flaws exist

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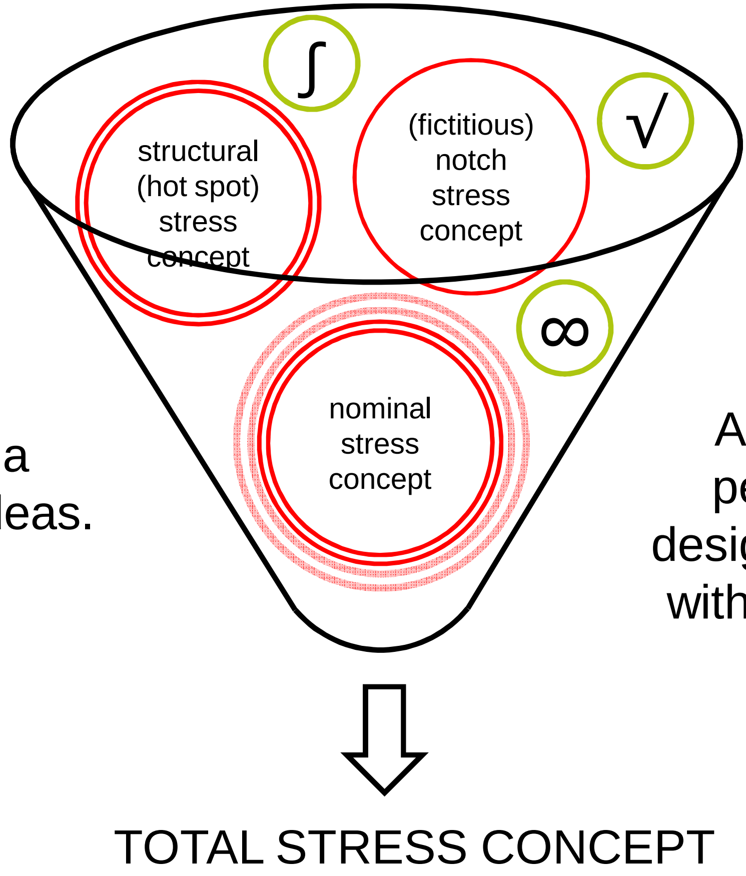
Idea

- Combine and extend the advantages of the different fatigue life prediction concepts for applicability in a design environment.

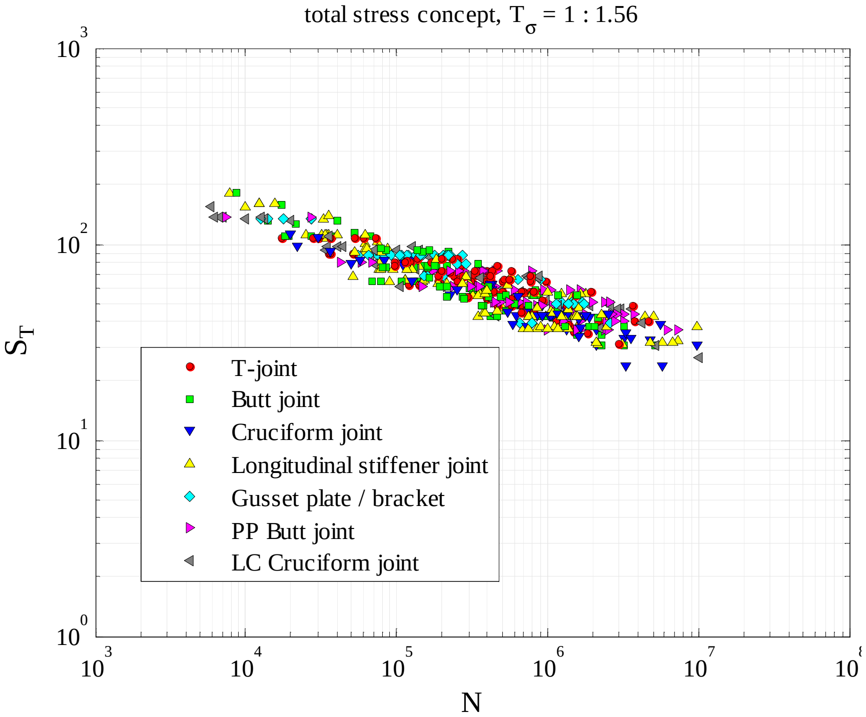


A good scientist is a person with original ideas.

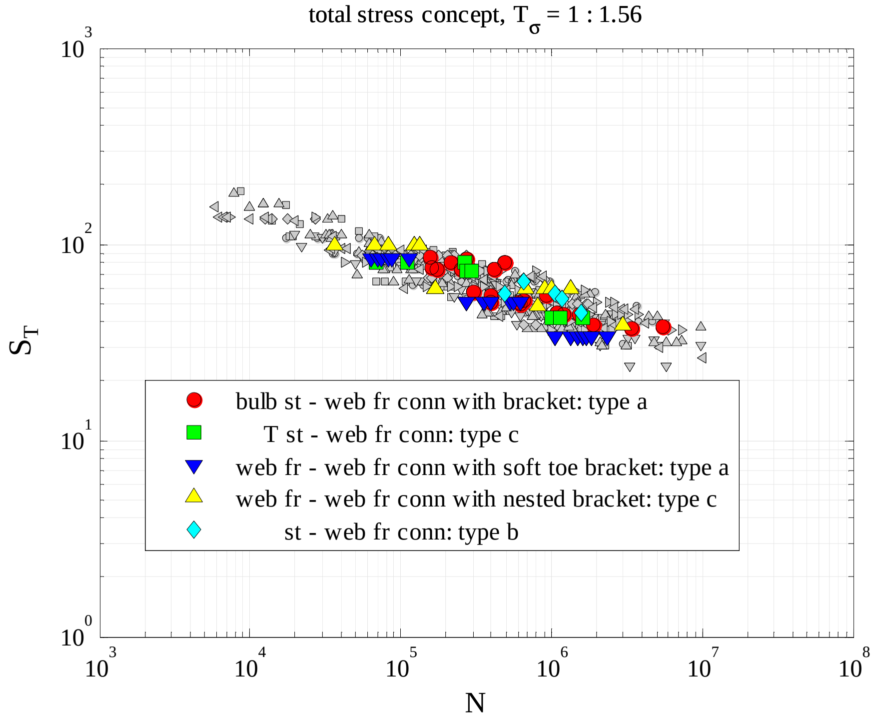
A good engineer is a person who makes a design(method) that works with as few original ideas as possible.

Total Stress Concept

Joint SN Curve Formulation



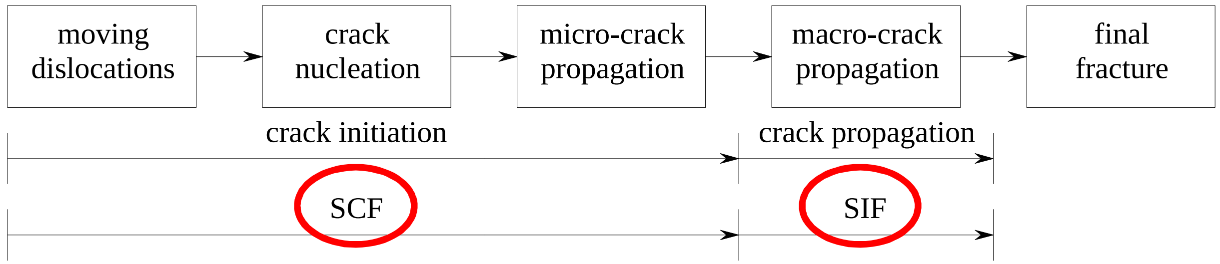
small scale specimen based



large scale specimen fit

Total Stress Concept

- Fatigue governing parameters



  - Stress Concentration Factor
  - Stress Intensity Factor

- Welding process induced flaws already exist

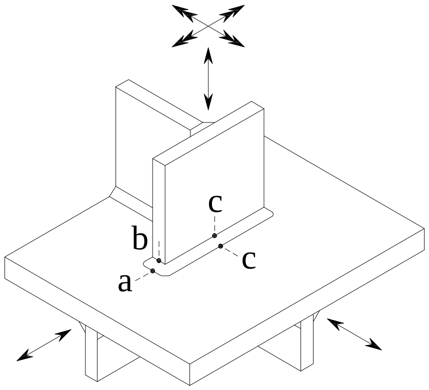
  ➡ fracture mechanics approach (LEFM, loading mode I)

- Include crack initiation period

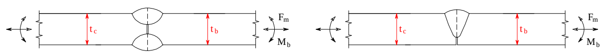
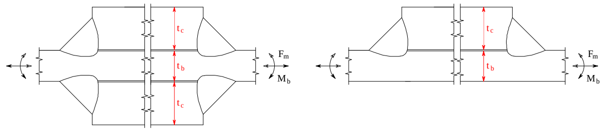
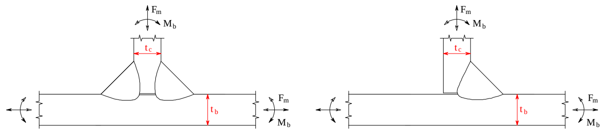
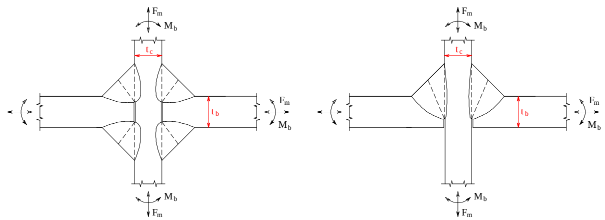
  ➡ modify SIF using SCF related notch stress distribution

Total Stress Concept

- Weld ends (HS type *a* and *b*)



- Basic welded joint formulations (HS type *c*):

			toe	root
➢ DS / SS butt joint:			4x / 2x	2x / 1x
➢ DS / SS cover plate:			4x / 2x	NC / NC
➢ DS / SS T-joint:			4x / 2x	2x / 1x
➢ DS / SS cruciform joint:			8x / 4x	4x / 2x

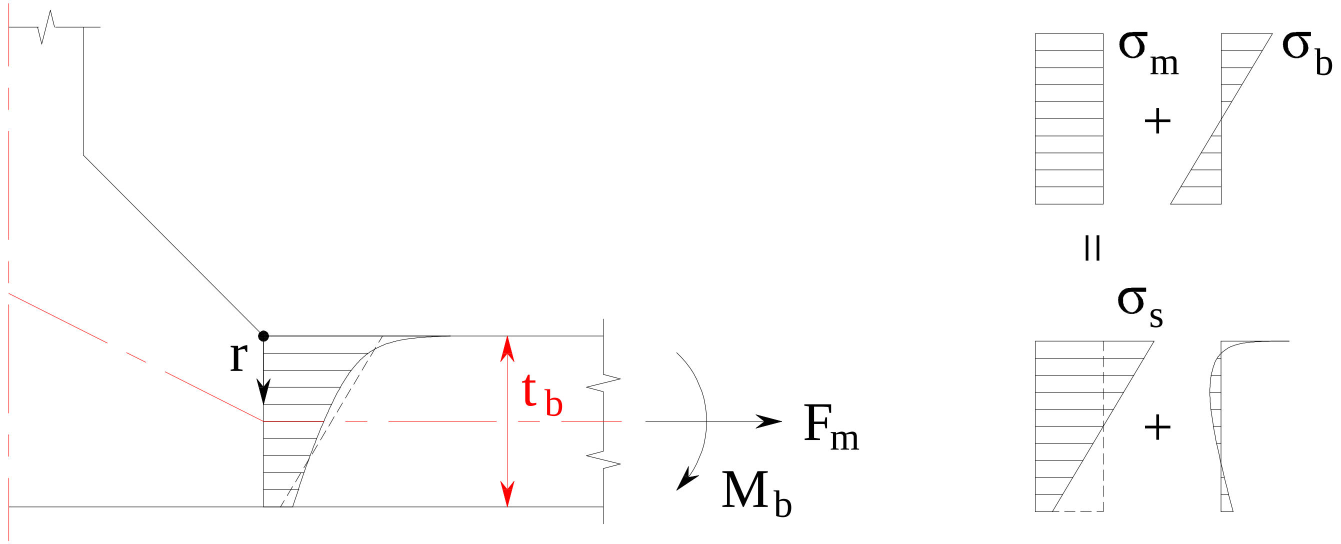
Total Stress Concept

- Notch stress formulation (force {F,M} induced, geometry and far field stress determined parameter):

equilibrium equivalent part
far field stress

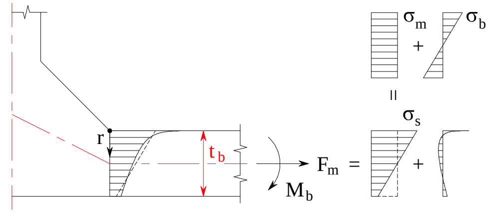
+

self-equilibrating part
weld geometry induced bending
+
Williams' asymptotic solution

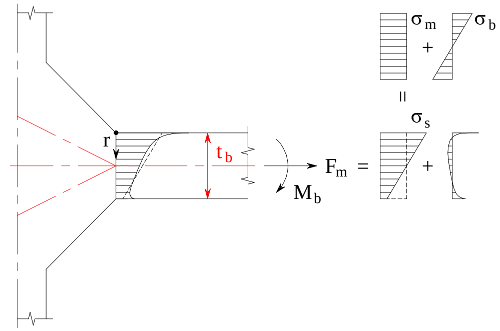


Total Stress Concept

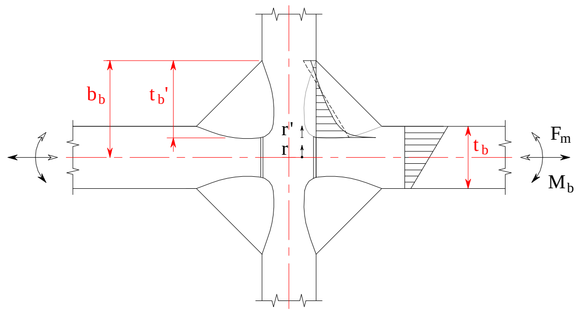
- Notch stress formulation, force {F,M} induced:
  - Notch angle $\alpha \neq \pi$ (fillet weld config): weld toe



    - Non-symmetry w.r.t. (t_b / 2), e.g. DS T-joint



    - Symmetry w.r.t. (t_b / 2), e.g. DS cruciform joint
  - Notch angle $\alpha = \pi$ (crack config): weld root / crack growth specimen



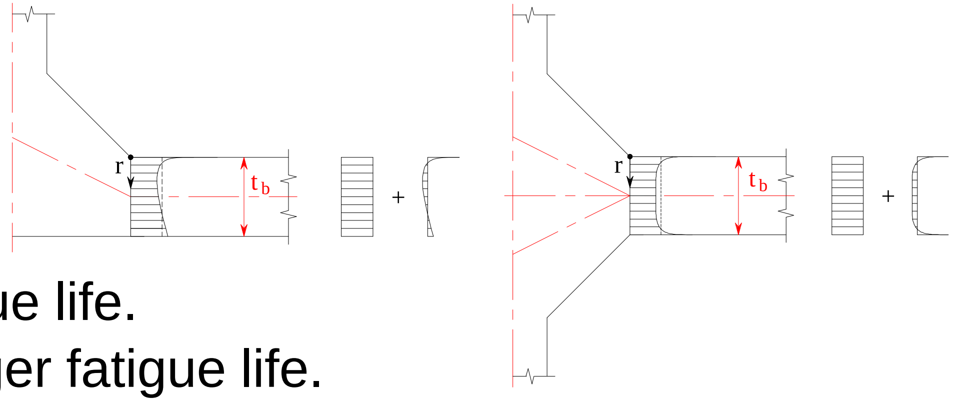
    - Non-symmetry, e.g. DS LC cruciform joint
    - Symmetry, e.g. DEN specimen

Total Stress Concept

- QUESTION 1: effects of self-equilibrating stress part

Consider weld toe failure of a DS T-joint and DS cruciform joint. Will there be any difference in fatigue life and if so, which joint has a longer fatigue life?

- The far field stress is the same for both joints (membrane state).
- Please note that the nominal-, hot spot- and fict. notch stress is the same.
- Regarding the DS cruciform joint, consider fatigue failure from 1 side.



A. Fatigue life is the same.
B. DS T-joint has longer fatigue life.
C. DS cruciform joint has longer fatigue life.
D. There is not enough information to answer this question.

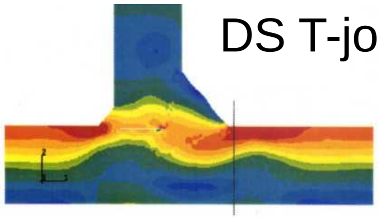
Total Stress Concept

- Residual stress formulation (welding induced):

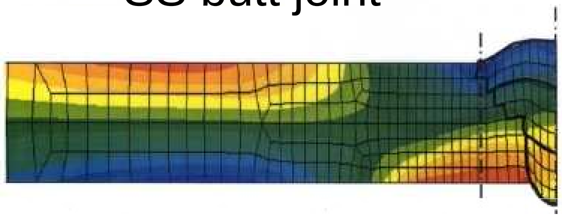
equilibrium equivalent
+
self-equilibrating part

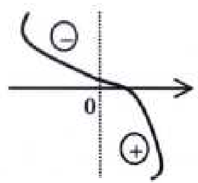
  - Non-symmetry w.r.t. (t_b/2):

DS T-joint



SS butt joint

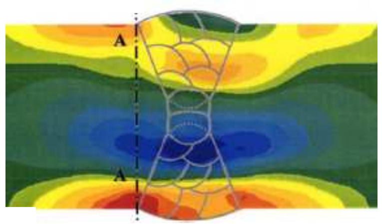


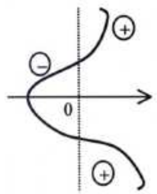


FE analysis, schematic

  - Symmetry w.r.t. (t_b/2):

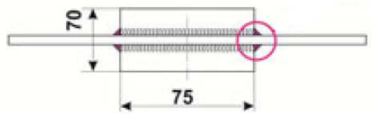
DS butt joint:



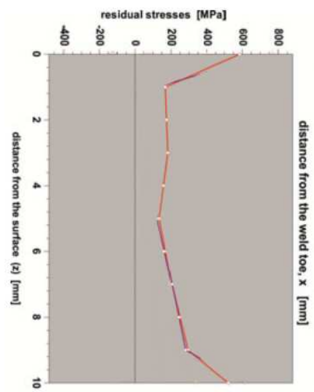


FE analysis, schematic

DS long. stiffener:



measured [Pagel, 2011]



Total Stress Concept

- Arc-welded joint: notch stress + residual stress formulation

Equilibrium equivalent part + self-equilibrating part

- Equilibrium equivalent part: force induced + welding induced
  - Force induced: $\{F_m, M_b\}$
  - Welding induced: membrane + bending (angular distortion)

measured / mean stress / fatigue strength *C* ← $S_s = C \cdot N^{-\frac{1}{m}}$ → measured / design value / fatigue strength *C*

- Self-equilibrating part:

→ hypothesis: distribution is similar for notch stress and residual stress!

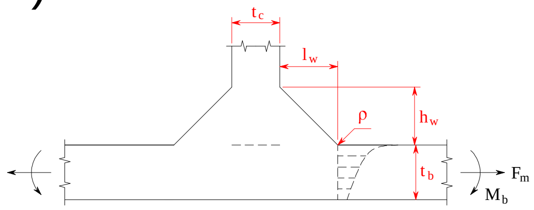
Total Stress Concept

- Notch stress formulation:

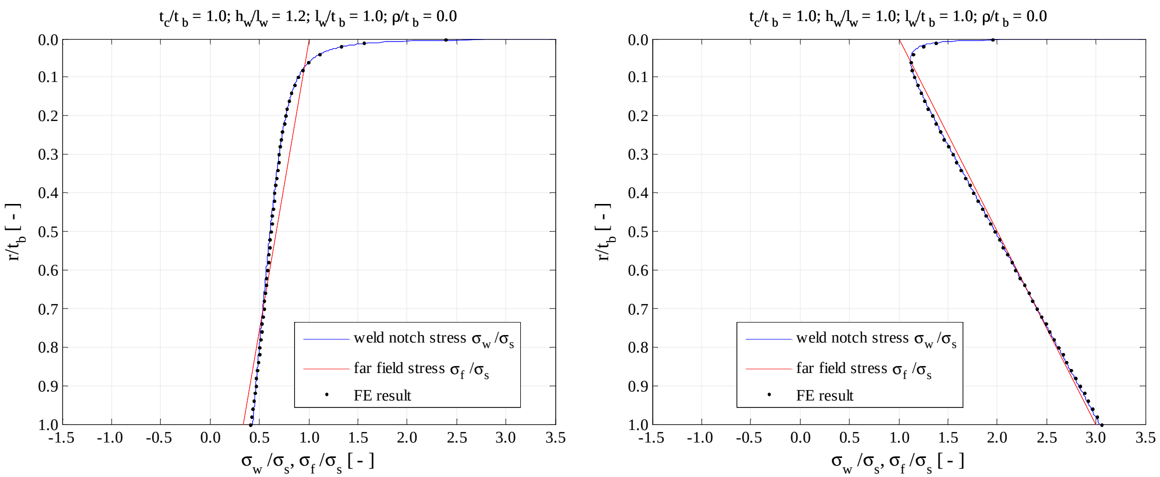
  - Analytical / characteristic (near) singularity / all geometry parameters

  - Related to linear far field stress distribution (FEM)

$$\sigma_s = \frac{f_m}{t_b} - 6 \cdot \frac{m_b}{t_b^{\,2}} \qquad R_s = -\frac{6 \cdot m_b}{6 \cdot m_b - t_b \cdot f_m}$$



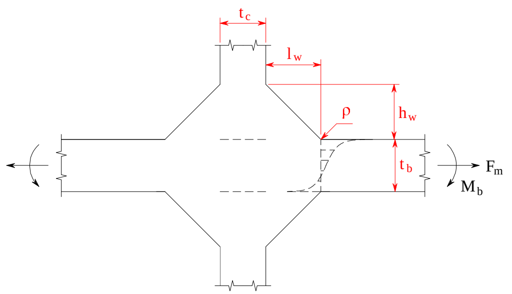
  - Example 1, ($\alpha \neq \pi$), non-symmetry: DS T-joint

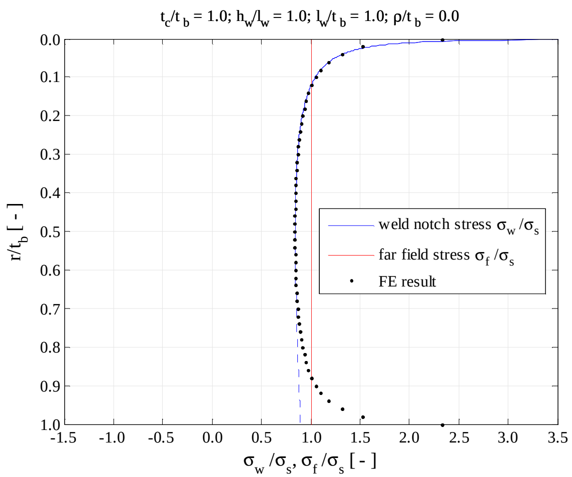


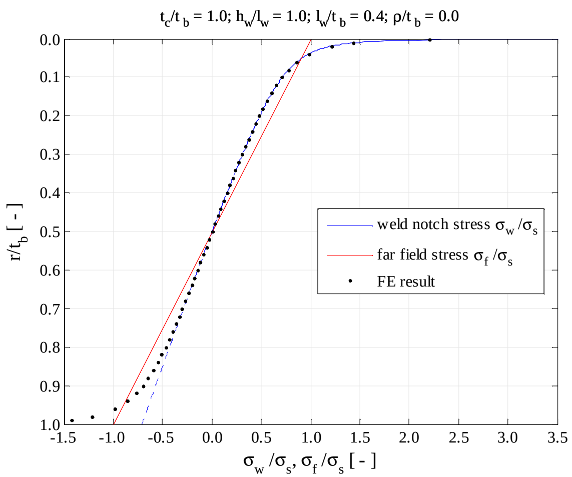
Total Stress Concept

- Notch stress formulation:

  - Example 2, ($\alpha \neq \pi$), symmetry: DS cruciform joint







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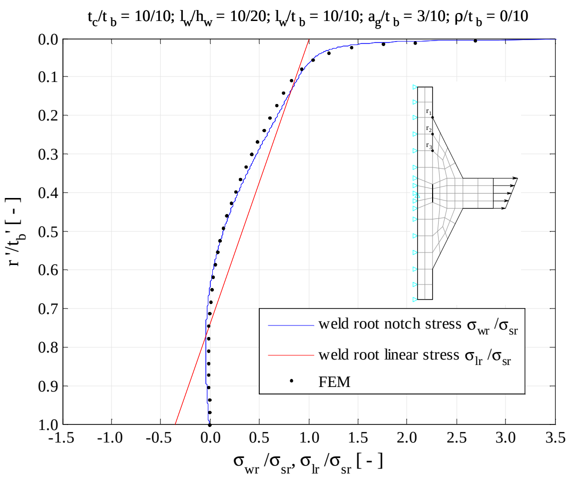
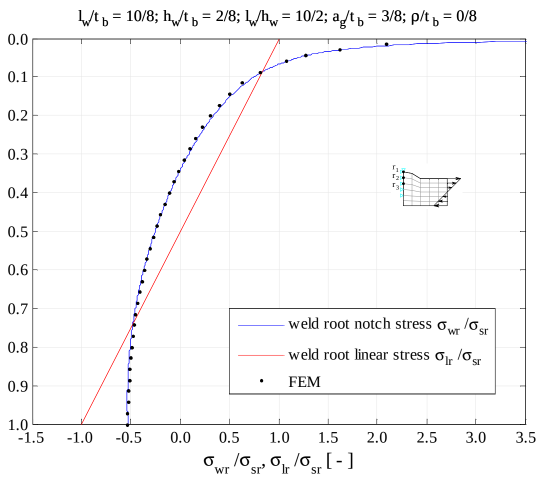
Total Stress Concept

- Notch stress formulation:
  - Example 3, ($\alpha = \pi$), non-symmetry: DS cruciform joint, SS butt joint
  - Assumed crack path: weld leg section (cr. joint), weld throat (butt joint)
  - Stress state mainly characterised by membrane and bending as well



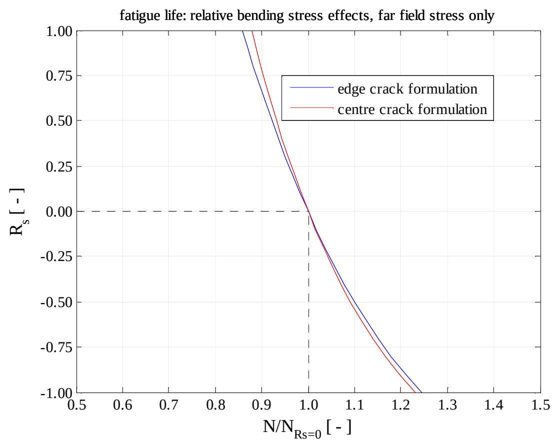


$\{\sigma_s, R_s\}$ still defines far field stress

Total Stress Concept

- Notch stress formulation: motivation

  - ➢ Fatigue life effects: equilibrium equivalent stress part $\{\sigma_s, R_s\}$



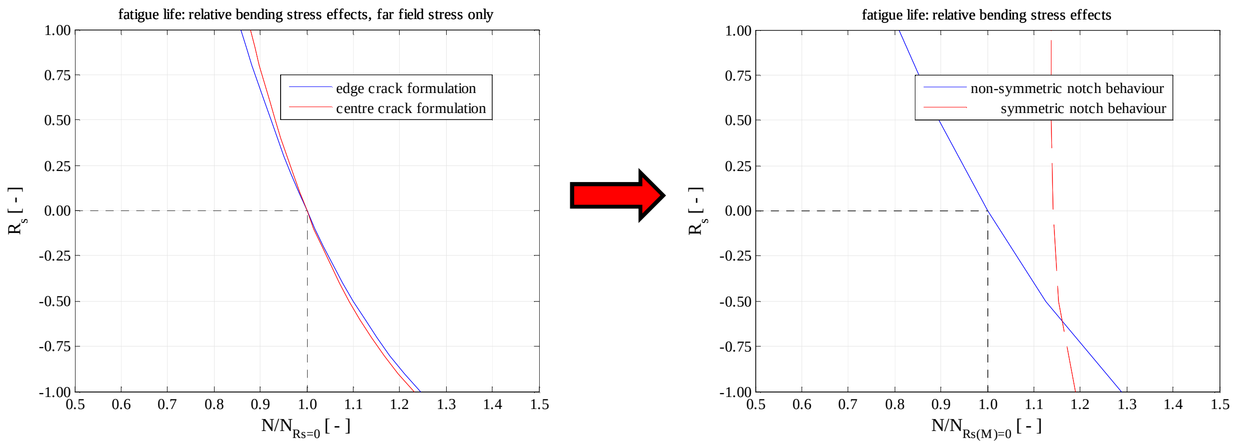
  - Pure bending shows better performance compared to pure membrane: $\frac{d\sigma_f}{dr}$

  - Non-monotonic behaviour means bad news

Total Stress Concept

- Notch stress formulation: motivation

  - ➢ Fatigue life effects: self-equilibrating part



edge crack formulation

answer Question 1: C

- Non-symmetry: weld geometry induced bending part amplifies effect
- Symmetry: 3 criteria, bending induced anti-symmetry require shift + scaling (no far field bending stress projection)
- Far field bending effect counter-acted by self-equilibrating stress (notch effect)

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Crack Propagation Model

- Stress Intensity Factor formulation K: generalised formulation not available for basic welded joints

$$K_I = Y_m \cdot Y_g \cdot \sigma \cdot \sqrt{\pi \cdot a} \quad (\alpha \neq \pi), \qquad K_I = M_k \cdot Y_g \cdot \sigma \cdot \sqrt{\pi \cdot a} \quad (\alpha = \pi)$$

- Equilibrium equivalent stress part: consistent with far field stress / solutions for simple geometries

➡ Geometry factor: Y_g

- Self-equilibrating unit stress part: notch effect / applied as crack face pressure

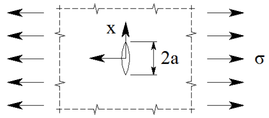
➡ Magnification factor: Y_m

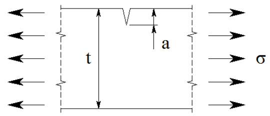
Crack Propagation Model

- Geometry factor Y_g: cracked geometry parameter

  - Covers macro-crack effects: finite thickness (and free surface)
  - Superposition principle: membrane + bending

$$Y_g = \left[\mathrm{sgn}(F_m) \cdot Y_{gm} + R \cdot \left\{ \mathrm{sgn}(F_m) \cdot Y_{gm} + \mathrm{sgn}(M_b) \cdot Y_{gb} \right\} \right]$$





  - Handbook solutions

- Weld root geometry correction M_k : cracked geometry, FEM

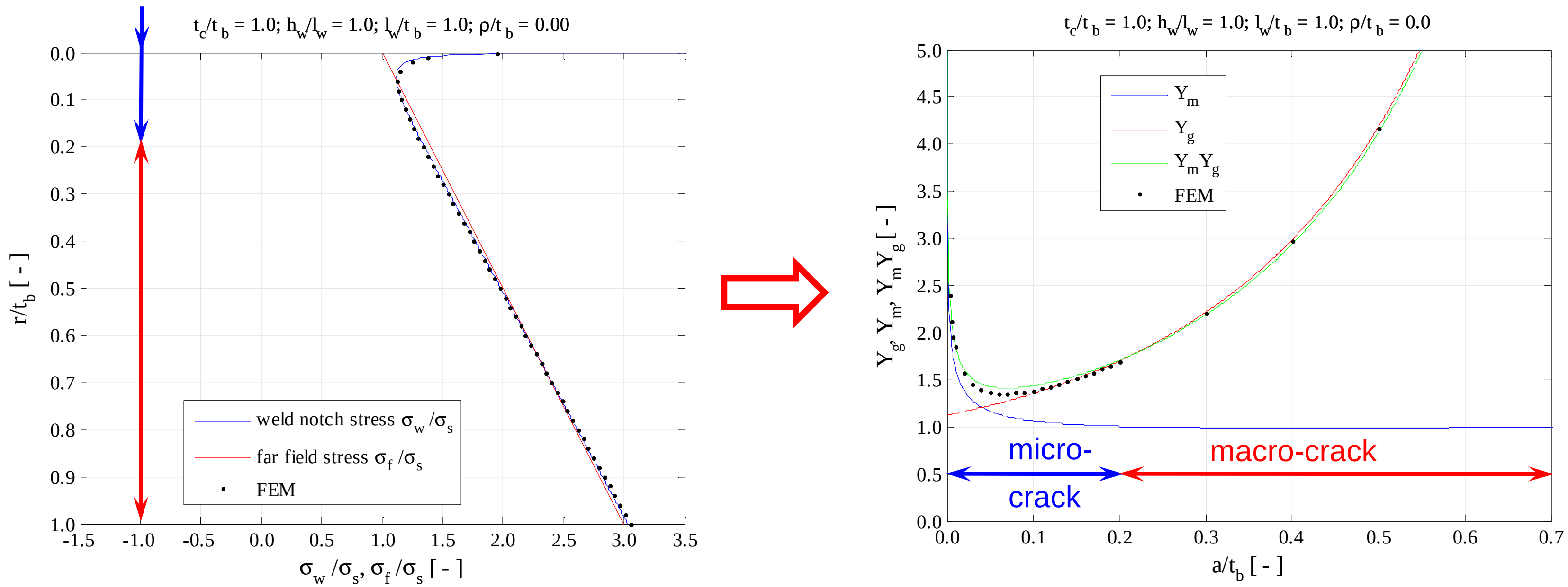
- Magnification factor Y_m: uncracked geometry parameter

$$Y_m = \left(\frac{2}{\pi} \right) \cdot \int_0^a \frac{\sigma(r)}{\sqrt{a^2 - r^2}} \, dr \qquad \sigma(r) = \frac{1}{\sigma_s} \cdot \left\{ \sigma_w \left(\frac{r}{t_b} \right) - 2 \cdot R \cdot \left(\frac{r}{t_b} \right) \right\}$$

Crack Propagation Model

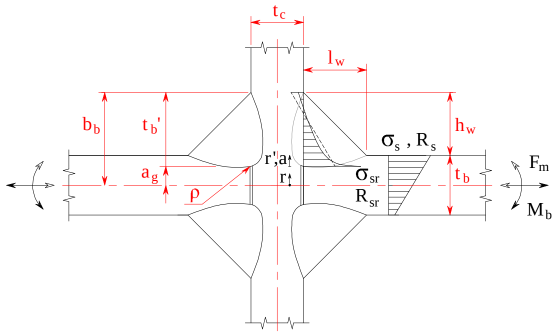
- Stress Intensity Factor example
  - Notch angle $\alpha \neq \pi$:

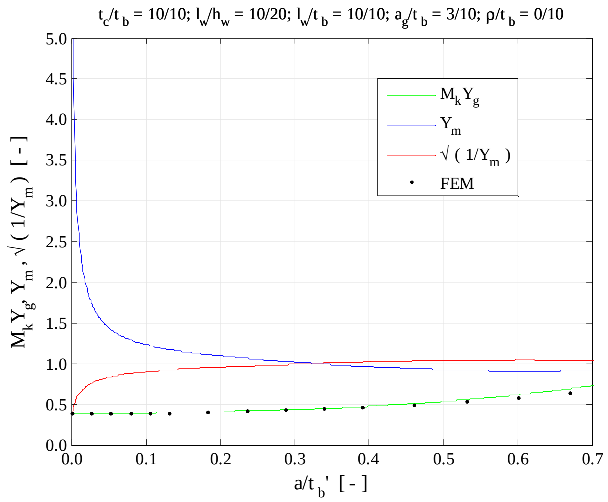
Y_m dominates $(a/t_b) \leq 0.2$	Y_g dominates $(a/t_b) > 0.2$
Williams' asympt. sol. dominates $(a/t_b) \leq 0.1$	
C_{gb} dominates $0.1 < (a/t_b) \leq 0.2$	



Crack Propagation Model

- Stress Intensity Factor example
  - Notch angle $\alpha = \pi$: geometry with gap a_g
    - SIF is $M_k Y_g$ determined; square root notch behaviour included in K by definition
    - $M_k Y_g < 1$, $b_b < t_b$
    - Y_m (notch effect) affects crack propagation!





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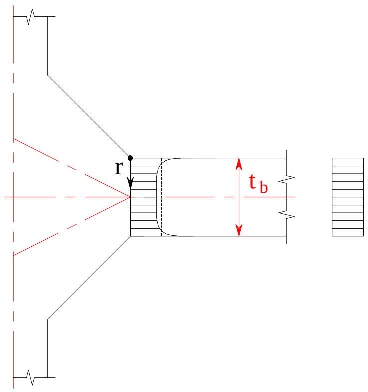
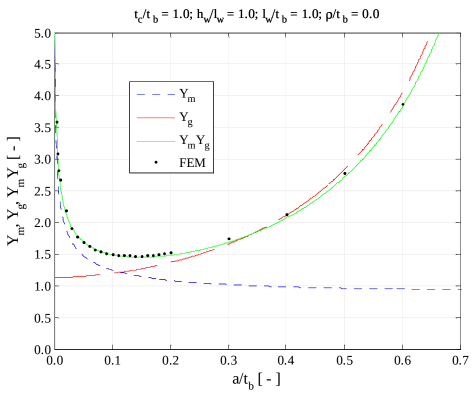
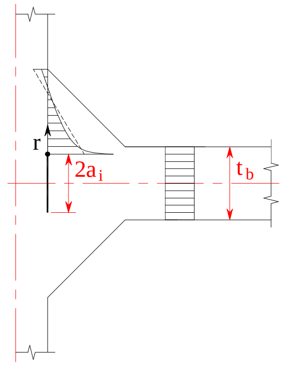
Total Stress Concept

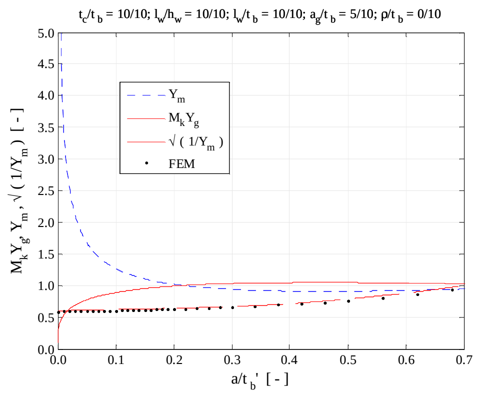
- QUESTION 2: fatigue life comparison for weld toe and weld root failure

Consider a DS cruciform joint. Will there be any difference in fatigue life for the weld toe and weld root failure case and if so, which one will be longer?









A. Fatigue life is the same.

B. Weld root has longer fatigue life.

C. Weld toe has longer fatigue life.

D. There is not enough information to answer this question.

Crack Propagation Model

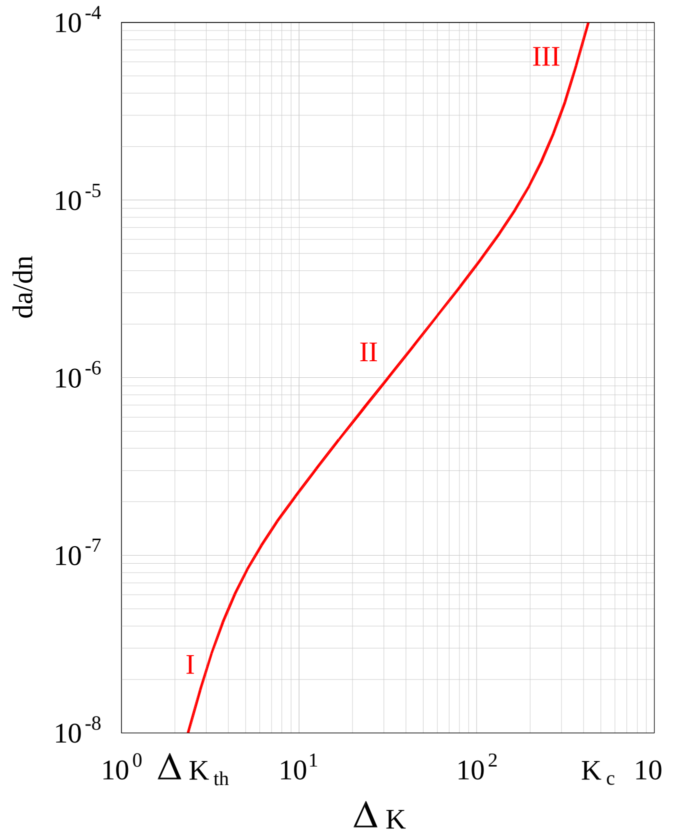
- Characteristic da/dn-ΔK curve (long crack growth)

- Paris-based two-stage model: ignore region III

$$\frac{da}{dn} = C \cdot \left\{1 - \left(\frac{\Delta K_{th}}{\Delta K}\right)\right\}^{\gamma} \cdot (\Delta K)^{m}$$

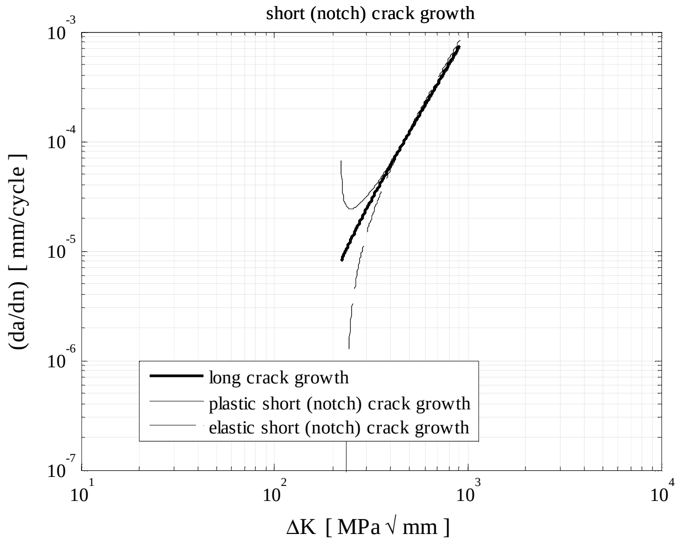
ΔK = crack driving force

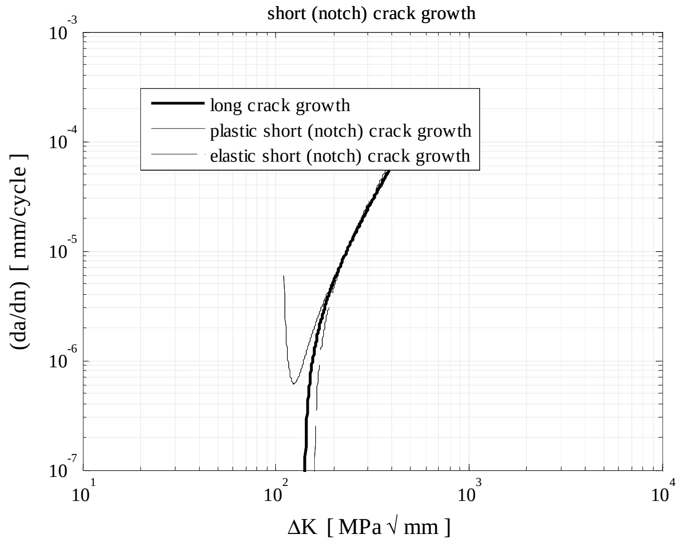
- Similitude hypothesis: da/dn depends only on (ΔK, ΔK_{th}, K_{max}, K_c)



Crack Propagation Model

- Crack growth at NOTCHES: elasticity/plasticity





- Frost-Dugdale model: da/dn = C·a

- Generalised Frost-Dugdale model (Jones et. al, 2008)

- non-similitude behaviour
- elastic crack growth at notch

$$\frac{da}{dn} = C \cdot a^{\left(1-\frac{m}{2}\right)} \cdot (\Delta K)^m$$

Crack Propagation Model

- Crack growth at NOTCHES: elasticity/plasticity

  - P. Dong: plasticity dominated micro-crack behaviour

$$\frac{da}{dn} = M_k^{\,2} \cdot \left(\Delta K_g\right)^m$$

  - Elasticity/plasticity criterion:

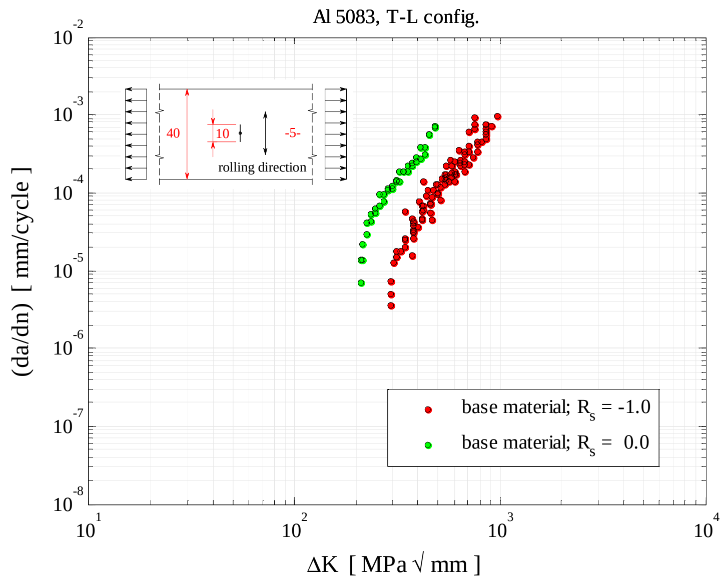
$$\left\lfloor \frac{r_{p,notch}}{r_{p,crack}} \right\rceil \begin{matrix} \geq 2 : plasticity \\ < 2 : elasticity \end{matrix}$$

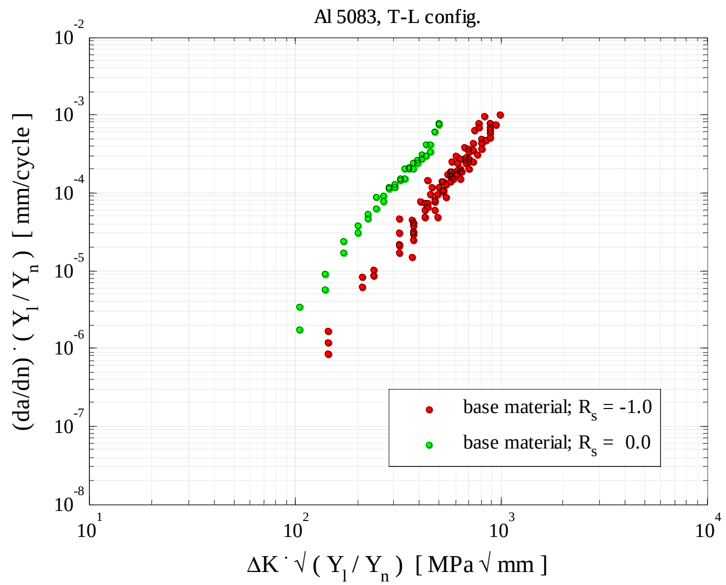
  - Model: work in progress because of slope dependency

$$\boxed{\frac{da}{dn} = C \cdot Y_m^{\,n-\frac{m}{2}} \cdot \left(\Delta K_g\right)^m} \qquad n = 1,2$$

Crack Propagation Model

- Crack growth at NOTCHES: elasticity/plasticity
  - Example: elastic behaviour

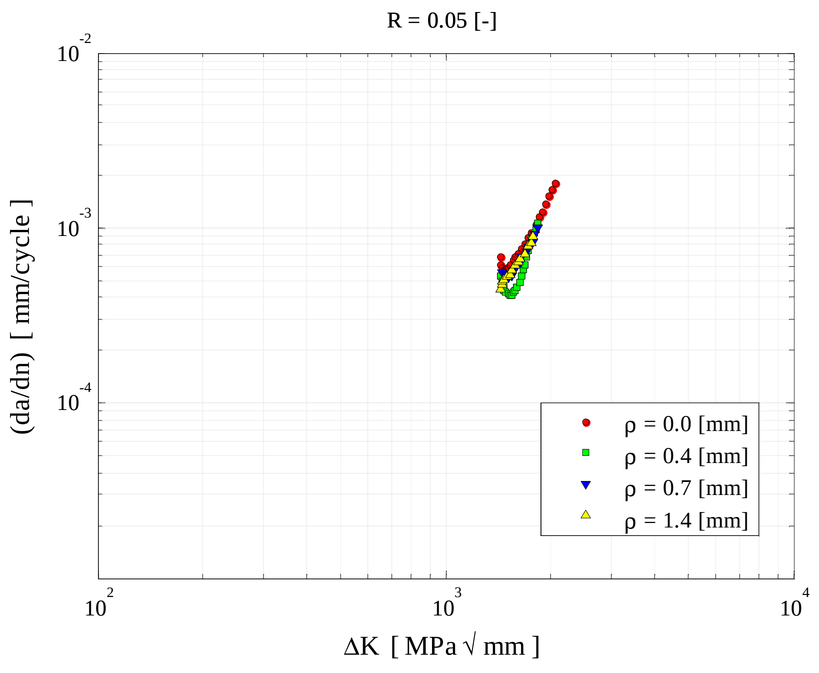


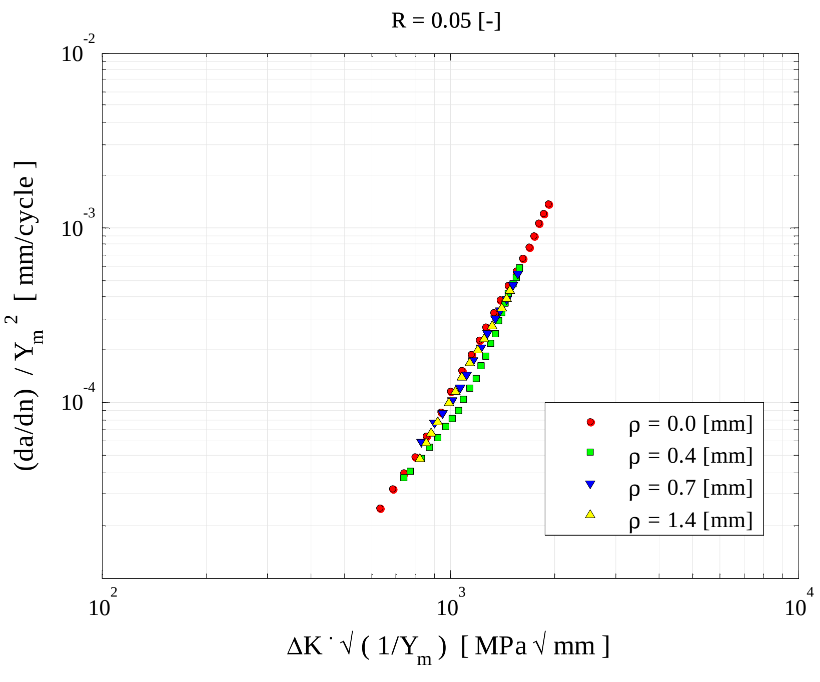


Crack Propagation Model

- Crack growth at NOTCHES: elasticity/plasticity

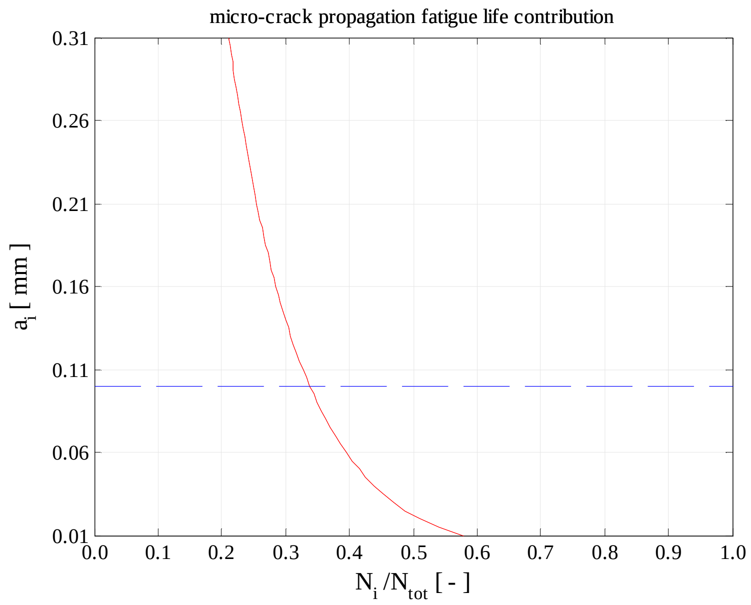
  - Example: plastic behaviour incl. notch radius effects

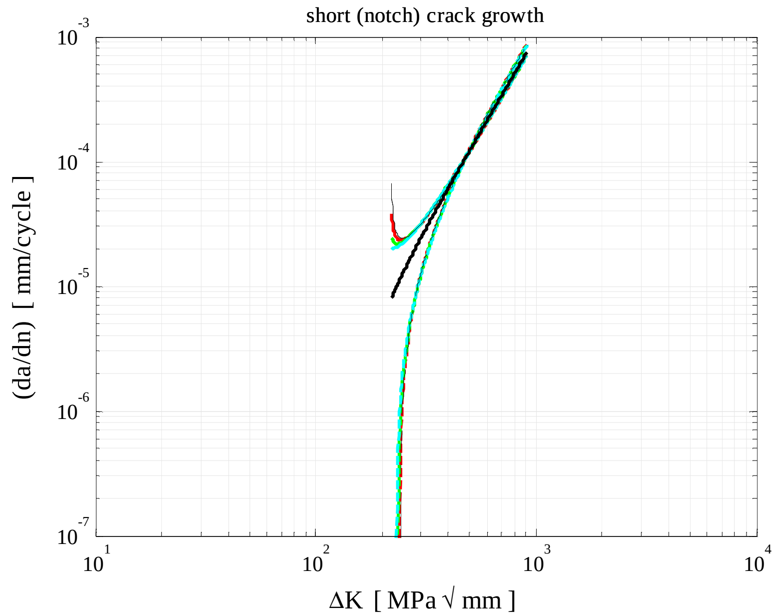




Crack Propagation Model

- Crack growth at NOTCHES:
  - Notch / micro-crack fatigue life effects and notch radius influence

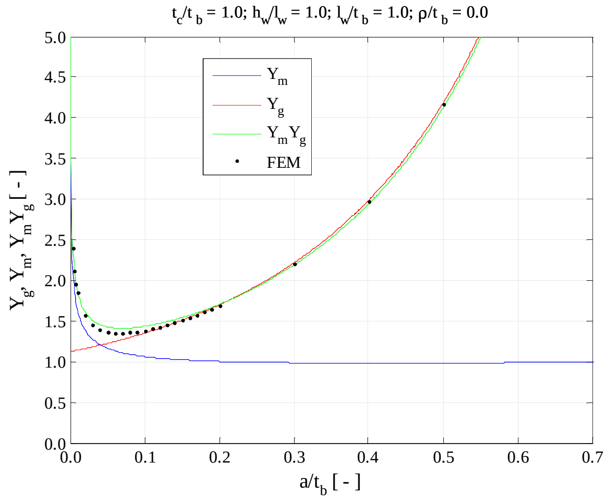


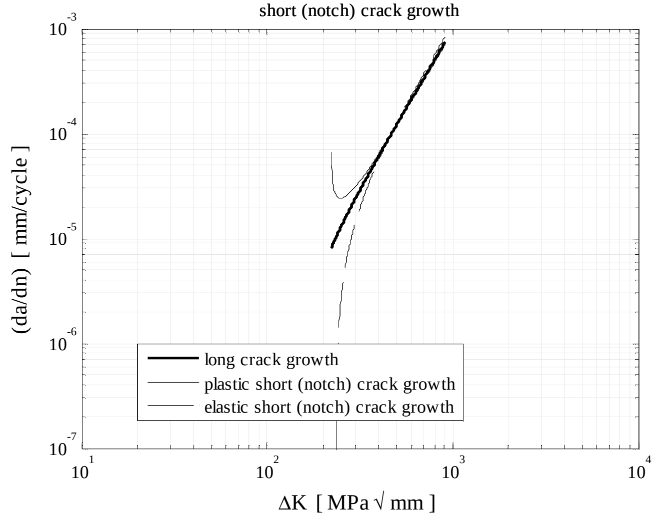


Total Stress Concept

- QUESTION 3: effect of final crack length

Consider a DS T-joint with SIF behaviour as shown. At what (dimensionless) crack length do you expect that > 90 [%] of the fatigue life is consumed?





A. 0.1 (a_f/t_b)
B. 0.3 (a_f/t_b)
C. 0.5 (a_f/t_b)
D. 0.7 (a_f/t_b)

Total Stress Concept

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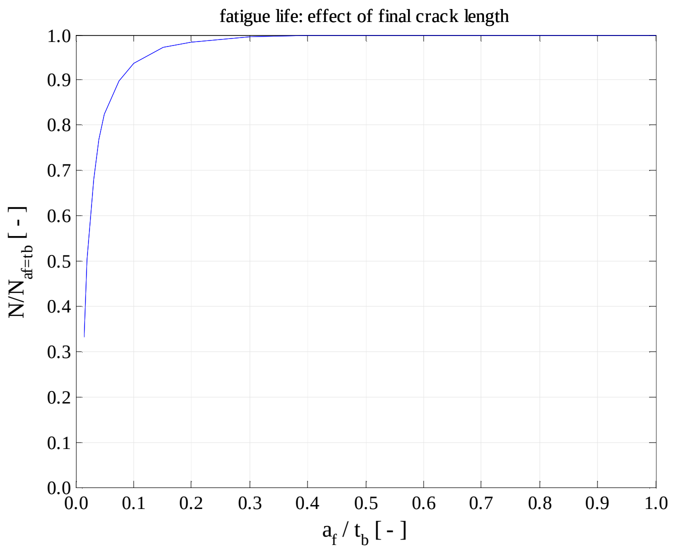

A. 0.1 (a_f/t_b)
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D. 0.7 (a_f/t_b)

Crack Propagation Model

- Fatigue test results suggest a non-linear mean stress dependency.
- Exponential relation (Kwofie, 2001):

generalization of several empirical models

$$\frac{\sigma}{\sigma_{R-1}} = e^{\left\{-\alpha \cdot \left(\frac{\sigma_R}{\sigma_{us}}\right)\right\}}$$

- First order approximation:

$$\left(\frac{\sigma}{\sigma_{R-1}}\right) = \left\{1 - \alpha \cdot \left(\frac{\sigma_R}{\sigma_{us}}\right)\right\}$$

  - Goodman, α = 1 ⇨ high-cycle fatigue: low σ / small σ_R

- High-cycle fatigue: low σ / large σ_R

  - Walker, $\alpha = \{\sigma_{us}/(\gamma \cdot \sigma_R)\} \cdot \ln\{(1-R)/2\}$

$$\left(\frac{\sigma}{\sigma_{R-1}}\right) = \left(\frac{1-R}{2}\right)^{\gamma}$$

TU Delft

Crack Propagation Model

- Walker's mean stress model using $\sigma_{eff} = \sigma \cdot e^{\left\{\alpha \cdot \left(\frac{\sigma_R}{\sigma_{us}}\right)\right\}}$:

$$\Delta\sigma_{eff} = \frac{\Delta\sigma}{(1-R_s)^{1-\gamma}}$$

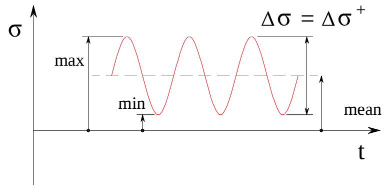
superior **curve fitting** results:

$\gamma \approx 0.5$ for $R \geq 0$
$\gamma = 0.0$ for $R < 0$

- Another definition of $\Delta\sigma_{eff}$ (Kim, Dong, 2006):

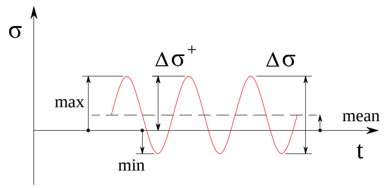
$$\Delta\sigma_{eff} = \sqrt{\sigma_{max} \cdot \Delta\sigma^{+}}$$

  - R ≥ 0: $\Delta\sigma_{eff} = \frac{\Delta\sigma}{(1-R)^{\frac{1}{2}}}$



$\Rightarrow$ $\gamma = 0.5$

  - R < 0: $\Delta\sigma_{eff} = \frac{\Delta\sigma}{(1-R)}$

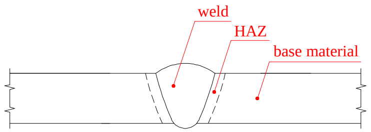


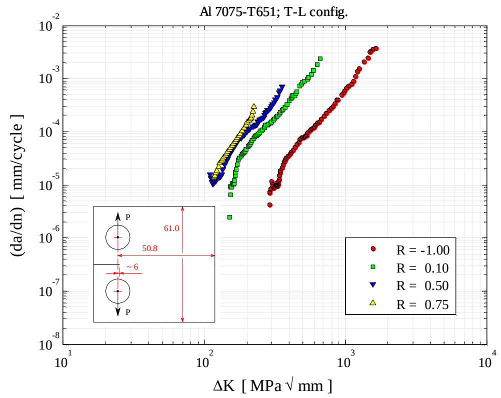
$\Rightarrow$ $\gamma = 0.0$

Walker's model: loading dependent mean stress

Crack Propagation Model

- Welded joints: alternating material zones
  - Weld (filler) material
  - Heat Affected Zone (HAZ)
  - Base (parent) material



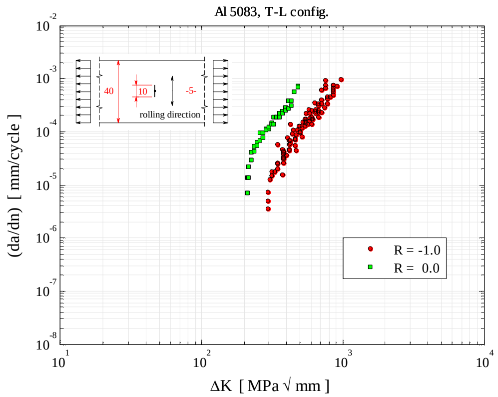


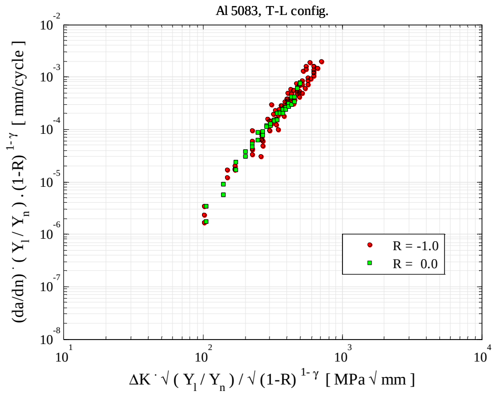
- Base material, loading induced mean stress:

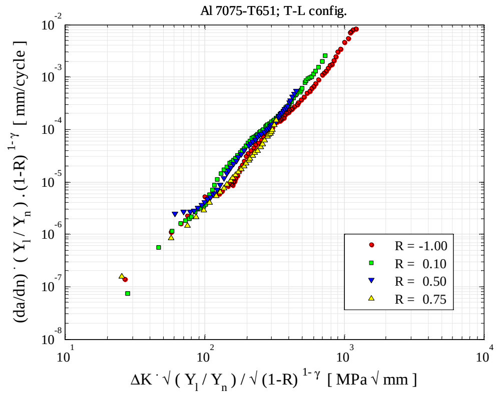
micro- **and** macro crack prop.

region affected according to Y_m:

$$\frac{da}{dn} = C \cdot \frac{Y_m}{(1-R)^{1-\gamma}} \cdot \left\{ \frac{Y_m^{-\frac{1}{2}}}{(1-R)^{\frac{1-\gamma}{2}}} \cdot \Delta K_g \right\}^m$$





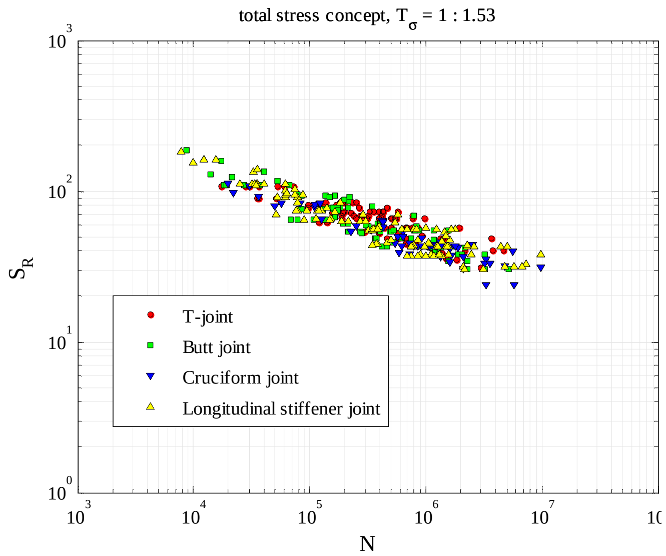


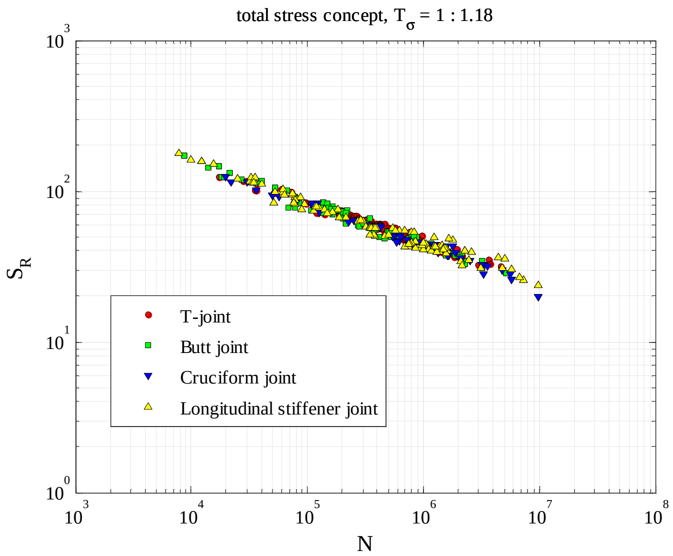
Joint SN Curve Formulation

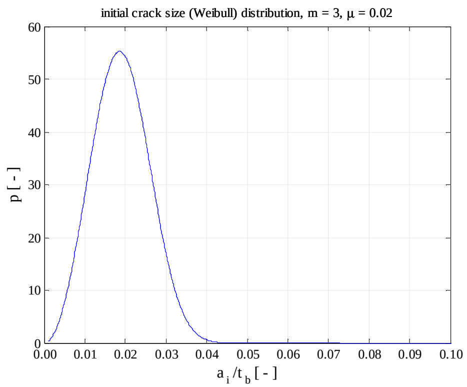
- Basquin type of equation:

$$S_T = C \cdot N^{-\frac{1}{m}} \quad \text{with} \quad S_T = \frac{\Delta\sigma_s}{t_b^{\frac{2-m}{2\cdot m}} \cdot I(R_s)^{\frac{1}{m}}} \quad \text{and} \quad I(R_s) = \int_{\frac{a_i}{t_b}}^{\frac{a_f}{t_b}} \frac{1}{\left\{ Y_m^{\,n-\frac{m}{2}} \cdot Y_g^{\,m} \cdot \left(\frac{a}{t_b}\right)^{\frac{m}{2}} \right\}} \, d\left(\frac{a}{t_b}\right)$$

- Initial crack size effect:







Joint SN Curve Formulation

- Mean stress effects:

The fatigue strength of welded joints is mean stress independent.
⇳
Welding induced residual stress acts as high-tensile mean stress.

➢ Micro-crack region: HAZ

welding induced high-tensile residual stress dominates loading induced part

➢ Macro-crack region: base material (weld toe) / weld material (weld root)

$$S_T = \frac{\Delta\sigma_s}{(1-R)^{\frac{1-\gamma}{2}} \cdot t_b^{\frac{2-m}{2\cdot m}} \cdot I(R_s)^{\frac{1}{m}}}$$

loading induced part only in macro-crack region

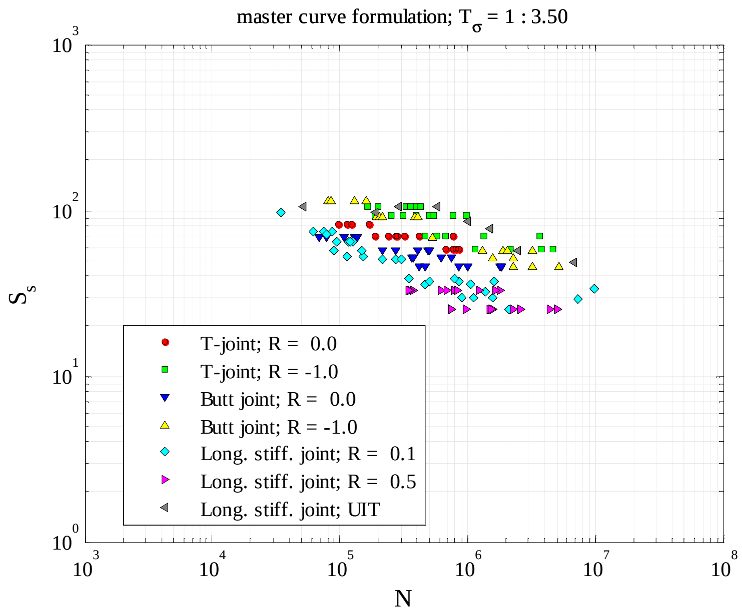
➢ Weld performance improvement (technique dependent) factor R_i

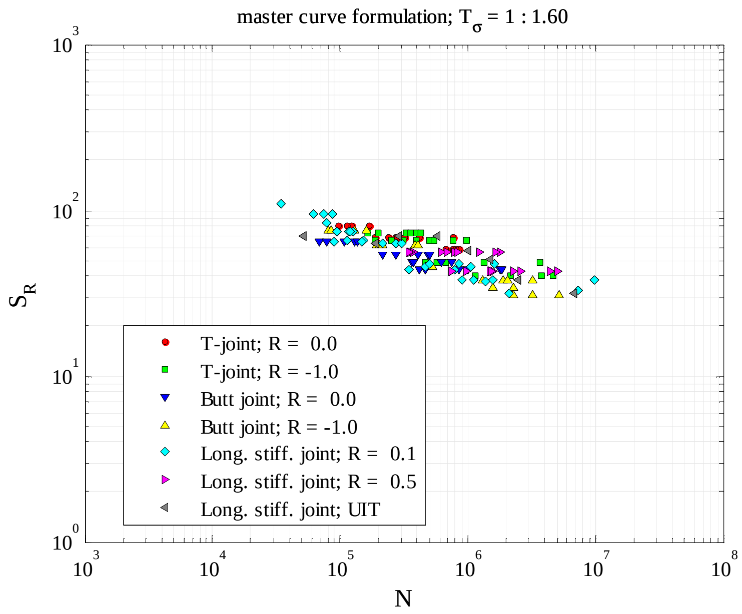
$$R_{eq} = 1-(1-R)\cdot(1-R_i)^{\frac{2\cdot(1-\gamma_i)}{m\cdot(1-\gamma)}}$$

micro-crack region correction and loading induced part in macro-crack region

Joint SN Curve Formulation

- Mean stress effects:

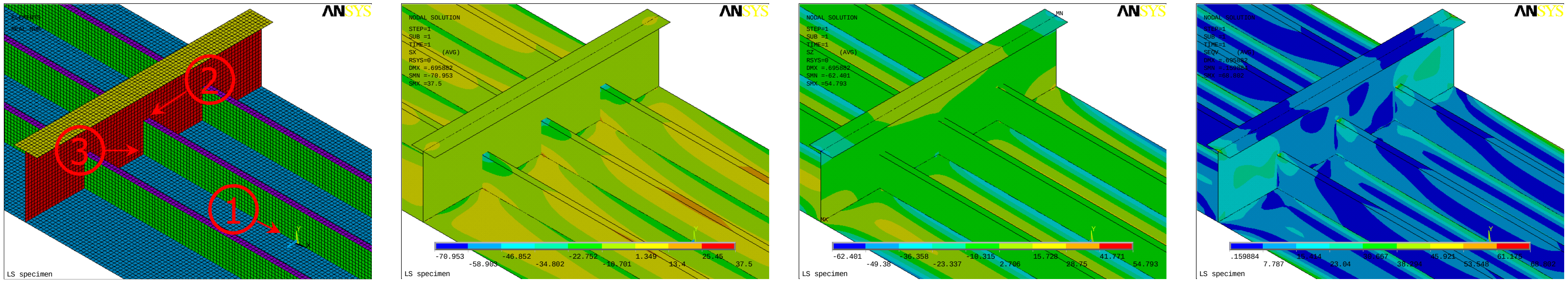




Joint SN Curve Formulation

- QUESTION 4: stress component for fatigue life calculation

Consider the structural response of the stiffened panel, loaded with space averaged pressure (sea side). The welding induced residual stress is assumed to be tensile. What stress value needs to be used at Pos. 2 for fatigue life calc.?

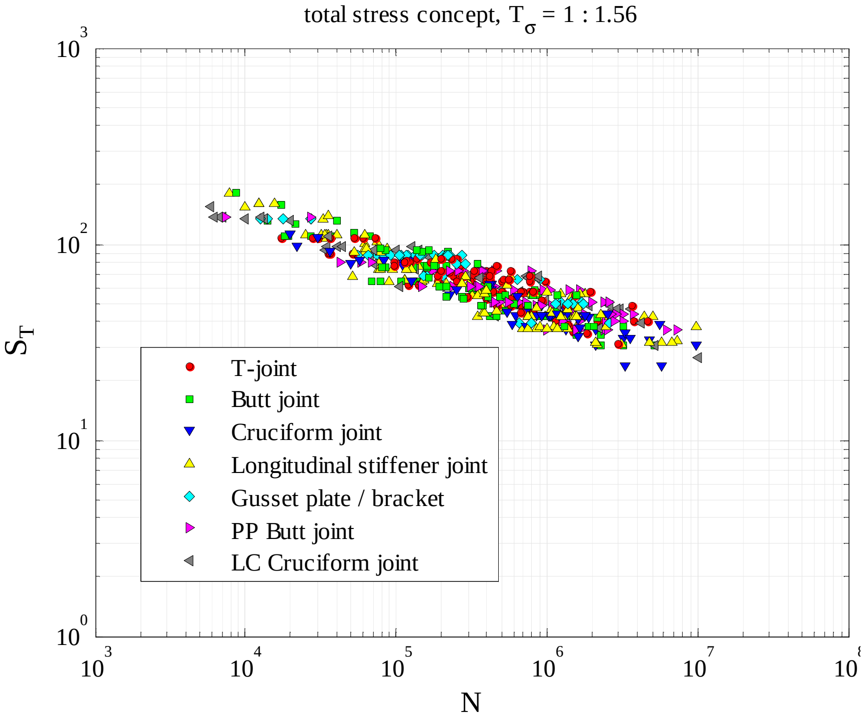


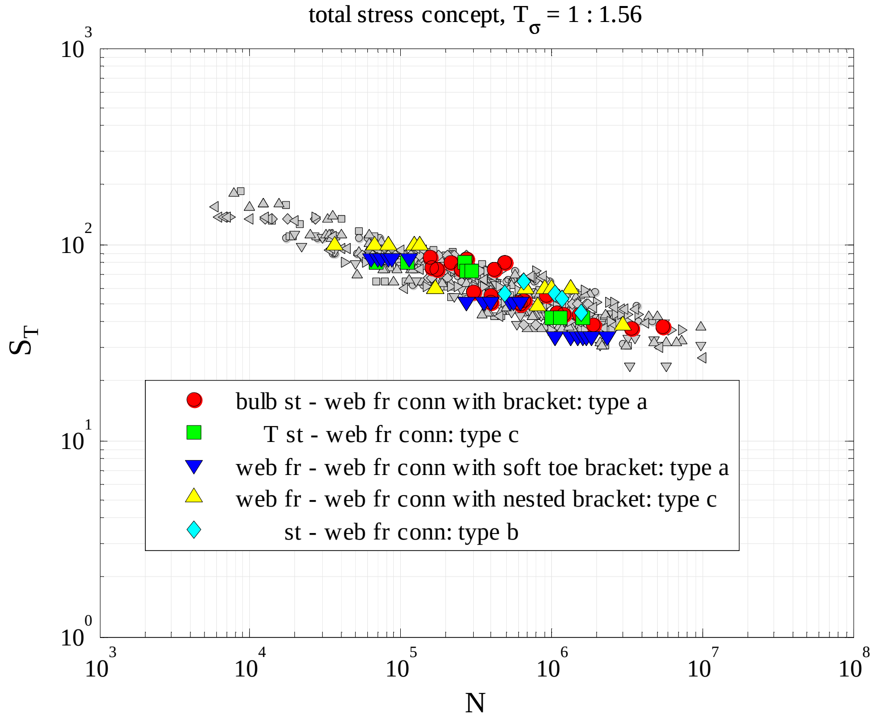
A. σ_x (mode I stress component)
B. σ_{VM} (Von Mises stress component)
C. $|\sigma_x|$ (absolute value of mode I stress component)
D. $|\sigma_x / 2|$ (absolute value of half mode I stress component)

Joint SN Curve Formulation

Joint SN Curve Formulation

Total Stress Concept
Joint SN Curve Formulation





small scale specimen based

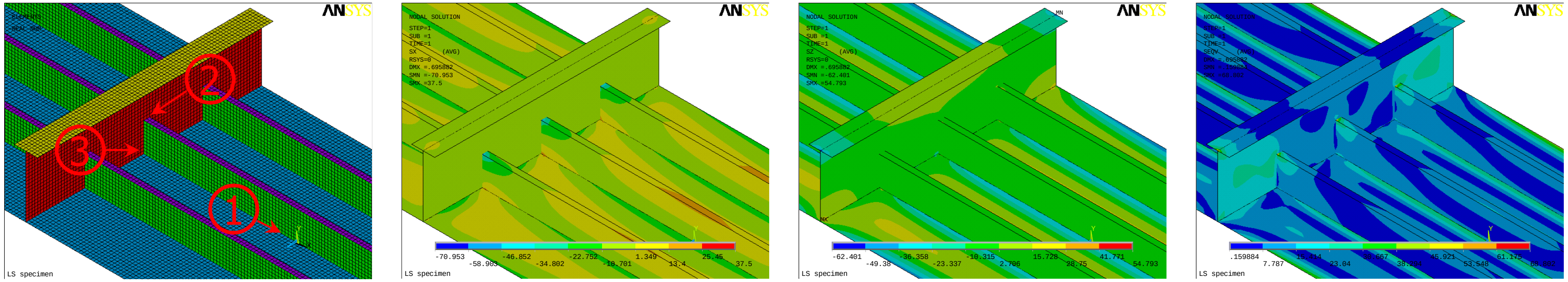
large scale specimen fit

Total Stress Concept

- QUESTION 6: effect of compressive stresses on fatigue life

Consider the structural response of the stiffened panel, loaded with space averaged pressure (sea side). At what weld location is the first crack expected?

- ➢ The welding induced residual stress is assumed to be tensile.



A. Position 1.
B. Position 2.
C. Position 3.
D. Position 1 and 3

Pos 1. σ_z = -42.0 [MPa]
Pos 2. σ_x = -63.5 [MPa]
Pos 3. σ_x = 15.5 [MPa]

Thank you for your attention!

QUESTIONS?